Method for Estimating Changes in Product Life Resulting From HALT Using Quadratic Acceleration Model

Cross Reference to Related Application

The present application is related to U.S. Patent Application Serial No. 09/557,672 entitled "Method for Estimating Changes in Product Life for a Redesigned Product", filed on April 25, 2000, and U.S. Patent Application Serial No. entitled "Method for Estimating Changes in Product Life Resulting From HALT Using Exponential Acceleration Model", filed concurrently with the instant patent application, and the disclosures of each are incorporated herein by reference.

Technical Field

The present invention generally relates to reliability engineering. It particularly relates to estimating product failure rates from HALT (Highly Accelerated Life Test) using quadratic acceleration model.

Background of the Invention

Over the years, practitioners of HALT (Highly Accelerated Life Test) and HASS (Highly Accelerated Stress Screen) have wanted a way to predict their product's MTBF (Mean Time Between Failure) from the results of HALT and HASS.

An important design characteristic of any commercial product (particularly electronic products) is the reliability of the product (system). The military broadly defines reliability as "the probability that an item will perform a required function without failure under stated conditions for a stated period of time" (see MIL-HDBK-721C, "Definition of Terms for Reliability and Maintainability"). Other related

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references on this subject matter include MIL-HDBK-217, "Reliability Prediction of Electronic Equipment"; MIL-HDBK-883, "Test Methods and Procedures for Microelectronics"; and Nelson, "Accelerated Testing: Statistical Models, Test Plans, and Data Analyses".

Indeed, the commercial viability of any product may be strongly determined by the product's reliability as potential users will not spend a significant sum of money on an unreliable product. The vital importance of product reliability spurred the emergence of Reliability Engineering as an engineering discipline that devotes itself to establishing, maintaining, and evolving the reliability of a product.

An exemplary useful reliability parameter is the product's failure rate (Failure In Time – FITS, failures per billion device hours) or the inverse measurement of Mean-Time-Between-Failures (MTBF). A failure is commonly defined as any event that prevents the product from performing its specified operations. A product's failure rate is the average rate at which the product will fail over its lifetime (e.g., 2 failures over 50 years). Conversely, the MTBF is total operating time divided by the number of failures over that period (e.g., 25 years/failure or 219,000 hours) which is generally regarded as the average length of time a user may reasonably expect the product to work before a failure occurs. Therefore, a primary design objective is to have a very low product failure rate or inversely a very high MTBF. For example, most commercial telephone switching equipment is designed for less than two hours of downtime in 40 years; undersea telephone systems are designed for less than three failures in 25 years; and personal computers are designed for a MTBF of at least 1,000,000 hours (assuming end-of-life replacement of component parts).

Therefore, an important reliability engineering procedure is to determine the MTBF for a product. Many reliability engineering methods determine MTBF by observing the product in the field during normal usage and by tracking the frequency of failures. However, this method is very costly and time-consuming and does not meet

the practical commercial needs of a product manufacturer who wants to accurately predict the MTBF early in the development process, which is not possible with currently available methods. Early prediction of MTBF allows the product manufacturer to make any necessary design changes at a low cost to ensure a product deployment with a very low failure rate. Without early prediction of MTBF, a product manufacturer must rely on very time-consuming field use data (requiring months and years of field testing) which delays product deployment and adversely affects future sales. Alternatively, product quality may be reduced if deployment cannot wait for the field use data or the field use data is no longer useful once it is finally obtained, thereby increasing the risk of distributing defective products to the market.

To provide early prediction of MTBF, product manufacturers commonly use a procedure standardized by the military described as the "Bill of Materials" (BOM) approach (Standard MIL 217 and MIL-HNBK-217F Reliability Prediction of Electronic Equipment). The BOM approach theoretically determines the product's MTBF by using the MTBF of each product component. For example, each individual resistor, integrated circuit and other component in a system may have a known MTBF, and the MTBF of the complete product can be calculated using these values. However, the BOM approach is notoriously unreliable because of interactions between product components and other factors which may include, but are not limited to, manufacturing process control, end-use environment, and design validation and ruggedness.

Thus, there exists a need to provide an accurate and early estimation of a product's MTBF, enabling product manufacturers to deploy relatively defect-free products.

Summary of the Invention

The present invention overcomes the previously mentioned disadvantages by providing an efficient method for early estimation of MTBF for a product from

"accelerated stress testing" data. The accelerated stress testing measures the response of the product operating in a first environment which is used to estimate the MTBF for the product operating in a second environment. In accordance with embodiments of the present invention, the first environment may be one or more test environments more likely to cause the product to fail than the second environment which is the normal operating environment for the product. The method disclosed herein advantageously may provide an efficient and early estimation of MTBF, enabling necessary design changes and reduction of development costs. An additional feature of the present invention provides an efficient technique for determining the life impact of a product redesign wherein the accelerated stress testing data may include data from a plurality of test environments.

The invention in one aspect is a method of estimating a life of a product, comprising: determining accelerated stress testing data for the product using the relationship $t_F = AF \times t_A^2$, the accelerated stress testing data representing the response of the product operating in a first environment; and calculating the mean-time-between-failures (MTBF) for the product operating in a second environment based on the accelerated stress testing data.

Brief Description of the Drawings

Fig. 1 is a block diagram showing an illustrative product development cycle.

Fig. 2 is a diagram showing quadratic acceleration factor in accordance with an embodiment of the present invention.

Fig. 3 is a diagram showing relationship between accelerated and field use times in accordance with an embodiment of the present invention.

Fig. 4 is a table showing MTBF estimation in accordance with an embodiment of the present invention.

Fig. 5 is a table showing MTBF estimation in accordance with an embodiment of the present invention.

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Fig. 6 is a table showing MTBF estimation in accordance with an embodiment of the present invention.

Detailed Description

AT&T Corp. has been a leader in the field of estimating changes in product life. For example, they have devised a process that allows one to begin with the Bill of Material (BOM) MTBF and predict an improvement in MTBF from HALT. This process has been named HALTPlus™. Some assumptions have been made for this process in order to provide accurate predictions. First, the λ factors in the reliability software database are adjusted from their default values so that they reflect realistic levels of the actual field failure rate for the parts. Second, the first HALT is used as a baseline to which future HALT results are compared.

FIG. 1 provides an illustrative example of a typical product cycle to which the present invention may be advantageously applied. It is noted that the product cycle shown is exemplary and numerous variations thereof may exist dependent on several factors, an example being product management procedures. The present invention is applicable to such variations as well. Thus, it is to be understood that the described product cycle is provided for explanatory purposes only and does not serve as a limitation on the scope of the present invention.

Typically, a product may be initially conceived and developed during the research and development stage 11. Following a successful proof of concept or feasibility study, the product enters the marketing stage 13 where it is commonly marketed to potential customers and/or subject to detailed market research assessments. After favorable marketability studies are performed, the product may be manufactured 15 and then via the sales phase 17 will be sold and distributed 19 to the customers identified in the manufacturing 15 and sales phases 17. Commonly, reliability testing performed during the manufacturing phase 15 uncovers product defects which must be corrected. This can result in costly delays to deployment. In embodiments described

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herein, the invention may be advantageously applied prior to the manufacturing stage 15 (e.g., the research and development stage 11) to discover latent product defects, thereby enabling efficient and low-cost modification of the product if necessary.

In accordance with embodiments of the present invention, the method described herein uses accelerated stress testing data to predict a Mean-Time-Between-Failures (MTBF) for a product. An exemplary type of accelerated stress testing that may be used is Highly Accelerated Life Testing (HALT). HALT is commonly used in conjunction with Highly Accelerated Stress Screen (HASS), a program used during manufacturing testing to uncover latent product defects and establish product quality control. HALT typically comprises a number of different stress regimens (conditions) designed to produce failures resulting from product usage in extreme operating environments. HALT advantageously provides a measure of the response of the product when subjected to the extreme operating conditions. The measured response may advantageously include the measured characteristics of the product wherein these characteristics may include, but are not limited to, gain, operating time, bandwidth, frequency, or other product characteristics.

Generally stated, the purpose of accelerated stress testing is to break the product so it can then be redesigned and improved. These different stress regimens (tests) can include, but are not limited to, multiple axis vibrational tests, rapid temperature transitions, high/low temperature limits, voltage margining, frequency margining, electrostatic discharge test (ESD), humidity tests, and any other test designed to find weak links in the product design. Commonly, HALT testing is carried out in environmental test chambers as part of the effort to uncover product weaknesses and then improve the product. These and other features of HALT and HASS are known to those skilled in the art and therefore not described in great detail.

In an embodiment, an additional feature of the invention provides a method for estimating the amount of change in product life resulting from the redesign of a product. The redesign, for example, may have been spurred by accelerated stress testing data

(e.g., HALT). This change in product life is referred to as Relative Life (R). It is to be understood that these and other terms used herein are solely used for purposes of clarity and should not be construed as any limitation upon the present invention.

The amount of change in product life can be described either in relative terms or, if an initial estimate of product MTBF exists, in terms of MTBF improvement. The change in product life, R, is relative to some unknown initial product life. This relative change represents a proportion (factor) increase or decrease in product life due to implemented design changes. The method described herein can also be used to estimate the absolute change in MTBF if an initial MTBF estimate is available. An initial MTBF is that which is characteristic of the product prior to implementation of any design changes. Relative Life multiplied by an initial MTBF estimate will yield a new MTBF estimate reflecting the results of design changes implemented during HALT.

Advantageously, the initial MTBF may be derived using BOM l values, wherein l represents the failure rate for different product components, in conjunction with compatible reliability software wherein the l factors in the reliability software database are adjusted from their default values so that they reflect realistic levels of actual field failure rate for the product components. For example, if the database shows l=70 FITS for a crystal oscillator (an exemplary product component), but recent field results indicate that the actual FIT rate has improved by 50%, then the l for the oscillator should be adjusted accordingly (e.g., lowered to l=35 FITS).

The method described herein is predicated on the idea that accelerated stress testing relates to field use conditions and that there is a mathematical relationship between the accelerated stress test and field use. Specifically, it is assumed that this relationship adequately maps from the accelerated stress test time line to the field use time line. In this embodiment, the accelerated stress testing data results from quadratic acceleration.

In accordance with this embodiment, the type of HALT process to which this method can be advantageously applied involves two separate HALTs (HALT 1, HALT

2). The first HALT is performed on the original unit (or a previous design of the current product) and the second HALT is performed on the redesigned unit that incorporates all necessary design changes indicated by the first HALT. Advantageously, HALT 1 and HALT 2 provide the same stress tests at the same stress levels, as applied to the original unit and the redesigned unit, but variations in the stress testing and stress levels can be factored into the MTBF estimation as described herein. Using this method of HALT, each stress regimen (test) is terminated once the operational limit is found. Furthermore, the derivation of this method assumes that the conditions (i.e., stress limits, chamber type, test suites, equipment, etc.) under which the second HALT is conducted are the same as the conditions of the first HALT. This assumption of similarity between HALT 1 and HALT 2 conditions is necessary to provide a valid comparison of the results for HALT 1 and HALT 2 that will yield an unbiased statistical estimate for relative life.

However, in practical applications of HALT, it often happens that some stress limits in HALT 2 are more extreme than the stress limits in HALT 1. For example, it may happen that the stress limits in Rapid Thermal Cycling (performed as part of HALT) are more extreme in HALT 2 due to the improved design. If this situation occurs, the application of this method may yield an underestimate of the true relative life. In other words, this method may yield a biased statistical estimate that is too small. Thus, if HALT 2 is run with limits more extreme than HALT 1, then the estimate obtained from the invention method should be interpreted as something less than the true amount of improvement in relative life. Lacking further information, the magnitude of the bias (i.e., the difference between the expected value of the estimate and the true value) is not known. Further details regarding this issue are described herein.

Description of Terms

Following is a description of the terms that will be used throughout the specification:

R — Relative Life representing the proportion change in product life resulting from design changes. R is the parameter of interest (i.e., the true but unknown value).

$\overline{R}$ — The statistic used to estimate R.

R^* — The natural log of R.

$\overline{R}^*$ — The statistic used to estimate R^*.

$\hat{R}_i$ — Estimated change in product life for the ith stress regimen.

$\hat{R}_i^*$ — The natural logarithm of $\hat{R}_i$.

$MTBF_{F2}$ — Mean Time Between Failure on field use time scale for redesigned unit.

$MTBF_{F1}$ — Mean Time Between Failure on field use time scale for original unit.

$MTBF_{A2}$ — Mean Time Between Failure on accelerated time scale for redesigned unit.

MTBF$_{A1}$ Mean Time Between Failure on accelerated time scale for original unit.

t_F Failure time on field use time scale.

t_A Failure time on accelerated time scale.

t_{A2i} Failure time on the accelerated time scale for the ith stress regimen for the redesigned unit.

t_{A1i} Failure time on the accelerated time scale for the ith stress regimen for the original unit.

AF   Acceleration Factor.

$\sigma_{\hat{R}_i^*}$ The standard deviation of $\hat{R}_i^*$.

$\sigma_{\bar{R}^*}$ The standard error of $\bar{R}^*$.

Quadratic Acceleration

Quadratic Acceleration is described by the equation $t_F = AF \times t_A^2$. In this equation, t_F is time on the field use time scale and t_A is time on the accelerated time scale (see Figures 2 and 3). AF is the Acceleration Factor appropriate for the particular stress regimen being used. It should be noted that these acceleration factors need not be known in order to apply the method described herein. As will be shown in the following derivation, these acceleration factors cancel out of all equations when calculating relative life.

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In applying the method described herein, it is assumed that an unmodified unit design (or previous design) can be represented by a population distribution for time to failure on the accelerated time scale. Furthermore, a unit with implemented design changes can be represented by a potentially different population distribution on the accelerated time scale. The difference between these two distributions will represent the amount of change resulting from the implemented design changes. More specifically, the ratio of the observed failure times from each distribution can be used to estimate relative change in product life (i.e., Relative Life).

Calculating Relative Life For a Single Stress Regimen

Relative Life (denoted by R) represents the factor (proportion) change in product life resulting from a design change or a group of design changes. As described herein for an embodiment, the parameter to be estimated is R. R is defined as the ratio of the field use MTBF of the redesigned unit to the field use MTBF of the original unit (or a previous design). The parameter R is given by equation 1.

$$R = \frac{MTBF_{F2}}{MTBF_{F1}} \qquad \text{eq. 1}$$

$MTBF_{F2}$ is the field use mean time between failures for the redesigned unit studied in HALT 2 and $MTBF_{F1}$ is the field use mean time between failures for the original unit (or a previous design) studied in HALT 1. The statistic that will be used to estimate this parameter is defined as the ratio of time to first failure of the modified design to time to first failure of the original design (or a previous design). By convention, the time to first failure for HALT 2 will always be placed in the numerator and the time to first failure for HALT 1 will be placed in the denominator. Thus, a

relative life value greater than 1 will indicate an improvement in product life, a relative life value of less than 1 will indicate a degradation in product life, and a relative life value equal to 1 will indicate no change in product life. It should also be noted that the calculated statistics for relative life are only estimates of the true change in product life and are subject to variability. This must be taken into account when interpreting the estimates. This will be discussed in more detail with reference to confidence intervals. The method described herein also includes a determination of confidence limits for R.

For a specific stress regimen, let t_{A1} represent the time to first failure during the stress test for the original (unmodified) unit. This value can be advantageously determined during the HALT 1 testing procedures. In this notation, the subscript A stands for Accelerated and the number 1 indicates the original (previous design) unit (i.e., HALT 1). HALT 1 advantageously represents the accelerated stress testing performed on the original unit (previous design). Let t_{A2} represent the time to first failure during the stress test for the modified (redesigned) unit. This value may be determined during HALT 2 as HALT 2 advantageously represents the accelerated stress testing performed on the modified (redesigned) unit. Similarly, t_{F1} and t_{F2} represent the times to first failures (hypothetical) under field use conditions for the unmodified and modified units, respectively.

Estimated Relative Life (denoted by $\hat{R}$) for a single stress regimen can be calculated from HALT data using the following equation:

$$\hat{R} = \frac{t^2_{A2}}{t^2_{A1}} \qquad\qquad \text{eq. 2}$$

Using t_{F2}/t_{F1} as an estimate for R as given in equation 1, equation 2 is derived from the simple relationship shown in equation 3.

$$\hat{R} = \frac{t_{F2}}{t_{F1}} = \frac{AF \times t^2_{A2}}{AF \times t^2_{A1}} = \frac{t^2_{A2}}{t^2_{A1}} \qquad \text{eq. 3}$$

Relative Life for a given stress regimen as calculated from the above equation represents an estimate for the relative amount of change in product life resulting from the group of design changes implemented as a result of the first HALT. A separate Relative Life value can be calculated for each stress regimen (test) in HALT wherein each regimen advantageously includes a different type of stress or stimuli being applied to the unit under test. An exemplary application of HALT includes five stress regimens (tests), examples being cold step stress (CSS), hot step stress (HSS), rapid thermal cycling (RT), step vibration (VIB), and combined environments (CE). Thus, if there are five stress regimens being used in the HALT, there will be five separate values for $\hat{R}$.

Exemplary CSS testing comprises the product beginning operation at a starting temperature (e.g., 20 °C) wherein the temperature is then decreased in successive steps (e.g., 10 °C steps) until the failure occurs. Similarly, exemplary HSS testing comprises the product beginning operation at a starting temperature wherein the temperature is then increased in successive steps until the failure occurs. Exemplary RT testing comprises applying continuous temperature increases and decreases to the product until failure occurs. Exemplary VIB testing comprises attaching the product to a vibration table wherein the product is subject to vibration in the X, Y, Z and rotational axes. Exemplary CE testing applies a pre-determined combination of accelerated stress tests (e.g., RT, VIB, etc.) to the product. It is noted there exist several variations of the type

of accelerated testing used and testing procedures described herein, and so while an exhaustive list is not included herein, it is to be understood that any such embodiments using a variation thereof are contemplated here and are within the scope of the present invention.

Calculating Relative Life Across All Stress Regimens

For calculating relative life, let $\hat{R}_i$ represent the estimated relative life from the ith stress regimen. A composite value for Relative Life (call it $\overline{R}$) can be obtained by combining the individual values for $\hat{R}_i$ from each stress regimen. $\overline{R}$ will be the estimate for R (the true but unknown relative life). Assuming that the time to failure values for each unit (modified and unmodified units) are exponentially distributed, $\overline{R}$ can be calculated as shown below. In the following notation, k is the number of stress regimens in the HALT.

$$\hat{R}_i = \frac{t^2_{A2i}}{t^2_{A1i}} \qquad\qquad \text{eq. 4}$$

$$\text{Let} \quad \hat{R}_i^* = \ln(\hat{R}_i) \qquad\qquad \text{eq. 5}$$

$$\overline{R}^* = \frac{1}{k}\sum_{i=1}^{k}\hat{R}_i^* = \frac{1}{k}\sum_{i=1}^{k}\ln(\hat{R}_i) \qquad\qquad \text{eq. 6}$$

$$\overline{R} = \mathrm{EXP}\left[\overline{R}^*\right] = EXP\left[\frac{1}{k}\sum_{i=1}^{k}\ln(\hat{R}_i)\right] \qquad \text{eq. 7}$$

As mentioned previously, $\overline{R}$ is a point estimate for R.

Calculating a Confidence Interval For R

A confidence interval for R can be calculated using the following results

showing the derivation which is described herein. The standard deviation for $\hat{R}_i^*$ is

given by,

$$\sigma_{\hat{R}_i} = 3.62 \qquad \text{eq. 8}$$

It follows that the standard error of $\overrightarrow{R}^*$ based on k stress regimens is,

$$\sigma_{\overline{R}^*} = \frac{\sigma_{\hat{R}_i^*}}{\sqrt{k}} \qquad \text{eq. 9}$$

It can be shown that the distribution of $\overrightarrow{R}^*$ is approximately normal. Let $z_{\alpha/2}$

represent the standard normal deviate having $\alpha/2$ of the area in the tail of the

distribution. A $(1-\alpha)*100\%$ confidence interval for R* is given by,

$$\overline{R}^* \pm z_{\alpha/2} \times \sigma_{\overline{R}^*} \qquad \text{eq. 10}$$

For example, a 90% confidence interval for R* based on k=5 stress regimens is given by,

$$\overline{R}^* \pm (1.645 \times 1.62)$$
$$\Downarrow$$
$$\overline{R}^* \pm 2.66$$

This confidence interval for R* can be converted to a confidence interval for R by simply taking the antilog of the limits shown above. Thus, a 90% confidence interval for R is given by,

$$EXP\left(\overline{R}^* - 2.66\right) \quad to \quad EXP\left(\overline{R}^* + 2.66\right)$$

eq. 11

Derivation of Results

The following material shows the derivation of the results used in the previously described method. This derivation assumes two independent random variables (X & Y) each of which have an Exponential Distribution with parameters $\lambda 1$ and $\lambda 2$, respectively. In order to simplify the notation, Y is being used in place of t_{A2} and X is being used in place of t_{A1}.

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The Exponential Density Function is given by,

$$f(x) = \lambda \cdot e^{-\lambda \cdot x}$$

The Gamma Density Function defined for x>0 is given by,

$$\Gamma(x, \alpha, \lambda) = \frac{\lambda^{\alpha} \cdot x^{\alpha - 1} \cdot e^{-\lambda \cdot x}}{\Gamma(\alpha)}$$

where, $\Gamma(\alpha)$ is the Gamma Function given by,

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha - 1} \cdot e^{-x} dx$$

For the special case where α=1, the Gamma Density Function reduces to the Exponential Density Function with parameter λ. Thus, for α=1,

$$\Gamma(x, 1, \lambda) = \text{Exponential}(\lambda)$$

The density functions for X and Y, written as gamma density functions are shown below:

$$fx(x) := \lambda 1^{\alpha 1} \cdot x^{\alpha 1 - 1} \cdot \frac{e^{-\lambda 1 \cdot x}}{\Gamma(\alpha 1)}$$

$$fy(y) := \lambda 2^{\alpha 2} \cdot y^{\alpha 2 - 1} \cdot \frac{e^{-\lambda 2 \, y}}{\Gamma(\alpha 2)}$$

Let z be a random variable where z=y/x (where 0<z<infinity). It can be shown through the method of convolution that the density function for the ratio of two independent positive random variables is

$$fz(z) = \int_{0}^{\infty} x \cdot fx(x) \cdot fy(x \cdot z) \, dx$$

Substituting the densities for X and Y into this equation gives

$$fz(z) := \int_{0}^{\infty} \left[x \cdot \left(\lambda 1^{\alpha 1} \cdot x^{\alpha 1 - 1} \cdot \frac{e^{-\lambda 1 \cdot x}}{\Gamma(\alpha 1)} \right) \cdot \left[\lambda 2^{\alpha 2} \cdot (x \cdot z)^{\alpha 2 - 1} \cdot \frac{e^{-\lambda 2 \cdot (x \, z)}}{\Gamma(\alpha 2)} \right] \right] dx$$

In the special case where Y and X are exponentially distributed both α_1=1 and α_2=1. Under these conditions, fz(z) reduces to

$$fz(z) := \frac{\lambda 1 \cdot \lambda 2}{(\lambda 1 + \lambda 2 \cdot z)^{2}}$$

From this, it follows that the distribution function for z is,

$$Fz(z) := \int_0^\infty fz(z)\, dz$$

$$Fz(z) := \int_0^\infty \frac{\lambda 1 \cdot \lambda 2}{(\lambda 1 + \lambda 2 \cdot z)^2}\, dz$$

$$Fz(z) := 1 - \left(\frac{\lambda 1}{\lambda 1 + \lambda 2 \cdot z}\right)$$

Let $W = \ln(Z^2)$. Using the method of "change of variable", the distribution of W is derived as follows:

$$G_w(w) = P(W \le w)$$

$$= P(\ln(Z^2) \le w)$$

$$= P(Z \le e^{w/2}) = F_z(e^{w/2})$$

Therefore,

$$G_w(w) = F_z(e^{w/2})$$

$$G(w) := 1 - \left[\frac{\lambda 1}{\lambda 1 + \lambda 2 \cdot e^{\left(\frac{w}{2}\right)}} \right]$$

Given the distribution function G(w), the density function for w can be determined as follows:

$$\left| g(w) := \frac{d}{dw} G(w) \rightarrow \frac{1}{2} \cdot \frac{\lambda 1}{\left(\lambda 1 + \lambda 2 \cdot \exp\left(\frac{1}{2} w\right)\right)^2} \cdot \lambda 2 \cdot \exp\left(\frac{1}{2} w\right) \right|$$

The density function for W can now be used to describe the mean and variance for W. Let the mean for W be denoted by E(w) and the variance for W be denoted by VAR(w).

$$E(w) = \int_{-\infty}^{\infty} w \cdot gw(w) \, dw$$

$$\left| E(w) := \int_{-\infty}^{\infty} w \cdot \left[\frac{1}{2} \cdot \frac{\lambda 1}{\left(\lambda 1 + \lambda 2 \cdot \exp\left(\frac{1}{2} \cdot w\right)\right)^2} \cdot \lambda 2 \cdot \exp\left(\frac{1}{2} \cdot w\right) \right] dw \right|$$

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Similarly, the variance for W is given as follows:

$$Var(w) = \bullet \int_{-\infty}^{\infty} (w - E(w))^2 \cdot gw(w) \, dw$$

$$\left| VAR(w) := \int_{-\infty}^{\infty} (w - E(w))^2 \cdot \left[\frac{1}{2} \cdot \frac{\lambda 1}{\left(\lambda 1 + \lambda 2 \cdot \exp\left(\frac{1}{2} \cdot w\right)\right)^2} \cdot \lambda 2 \cdot \exp\left(\frac{1}{2} \cdot w\right) \right] dw \to \frac{4}{3} \cdot \pi^2 \right|$$

$$\frac{4}{3} \cdot \pi^2 = 13.159$$

Thus, the variance of W is 13.16. Therefore, the standard deviation of W is 3.62 as stated in equation 8 in the section on calculating a confidence interval for R. It has been shown that this result for the variance of W is independent of $\lambda 1$ and $\lambda 2$. Thus, the width of the confidence limits for R are not dependent on the failure rates or MTBF's for the two populations involved.

Calculating MTBF for the Redesigned Unit

A MTBF estimate for the redesigned unit can be calculated if an initial MTBF estimate for the unmodified unit is available. An initial MTBF for the unmodified unit can often be obtained via a parts count method (e.g., Bill of Materials - BOM). MTBF for the redesigned unit can be calculated as follows:

$$MTBF_{Redesign} = \overline{R} \times MTBF_{initial} \qquad \text{eq. 12}$$

Confidence limits for MTBF can be calculated by substituting the previously calculated limits for R into the above equation.

Estimation of Product Life

Application of the method described herein to actual HALT results for three products (Unit A, Unit B, Unit C) is shown in Figures 4, 5 and 6. As shown in the figures, five exemplary HALT stress regimens that were used include CSS (Cold Step Stress), HSS (Hot Step Stress), RT (Rapid Thermal), Vib (Vibration Step Stress), and CE (Rapid Thermal combined with Vibration Step Stress). Actual results are shown for three different units and all failure times are measured in hours. The BOM MTBF is used as the MTBF for the original product (previous design).

For Unit A (see FIG. 4), the estimate for relative life indicates that the unit life has improved by a factor of 2.46. Generally, it may be estimated that the redesigned unit is 146% better than the original unit in terms of product life. It is recognized that 2.46 is only an estimate for R and that the true value for the amount of change is most likely different from this estimate. The 90% confidence limits give upper and lower bounds on where the true value for R probably lies. In this example, there is a 90% probability that the true value for R is larger than 0.17 and smaller than 35.10. Since values less than 1 are contained inside this interval, it is not possible to conclusively state that the product life has improved.

During the course of accelerated stress testing, it is assumed that only four physical units are being evaluated during HALT which gives rise to the uncertainty.

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Generally, the failure rate of a product is a function of the product's operating environment. As the operating environment becomes harsher, the product's failure rate will increase. Therefore, commonly a product's field failure rate is low ($\leq 1\%$) when operating in a low-stress environment (e.g., office environment at room temperature) which consequently makes the probability of finding a failure low as well. HALT testing improves the probability of finding a failure without requiring a substantial number of test units. Assuming four units are being tested, the theoretical probability of finding a failure during testing is 25% (one in four units). With experience from previous HALTs and the assumptions described herein, it is determined that this theoretical probability is actually higher in practice as the physical sample size of four units actually behaves as substantially more than four units when subjected to HALT testing, HALT being an exemplary accelerated stress testing method. For example, if a failure mode has a field failure rate of 1%, then the probability of finding at least one failure in a sample of n=4 units is 4%. A failure mode refers to the specific type of failure uncovered (e.g., solder joint, bad component, etc). If application of HALT testing increases the product failure rate (e.g., failures occur more frequently) by a factor of 10, then the HALT failure rate will be 10% (10 x 1%) and the probability is 36% of finding at least one failure in HALT using a sample of n=4 units wherein the determination of the increased probability may be based on probability theory known in the art. At the field failure rate of 1%, it would take a sample size of 42 units to give a probability of 34% of detecting at least 1 failure. This assumption of the increase in sample size has been generally referred to as the "Virtual Sample Size".

Applying the factor 2.46 to the initial MTBF gives an MTBF for the redesigned unit of 734221 hours. Once again, this must be viewed as an estimate. The confidence limits for R could be applied to the initial MTBF estimate to give approximate confidence limits for the true MTBF for the redesigned unit.

It is noted that the method described herein may be advantageously embodied in a software computer program compatible with any computer operating system. In an exemplary embodiment, the accelerated stress testing data may be used by the program (inputted either manually or automatically) to calculate the MTBF (including R) for the product.

Effect of Dissimilar Stress Limits

It has been asserted that if the stress limits for HALT 2 are more extreme than the stress limits for HALT 1 then the estimate for relative life underestimates the true value for relative life. The following is a proof of this assertion and is predicated on the assumption that more extreme stress limits on a given stress regimen imply a greater acceleration factor. Let AF_2 represent the acceleration factor for a given stress regimen under HALT 2 and let AF_1 represent the acceleration factor for the same stress regimen under HALT 1. Under the situation where HALT 2 has more extreme stress limits than HALT 1, AF_2 is greater than AF_1.

Recall that the ratio t_{A2}/t_{A1} for a given stress regimen is the statistic used to estimate

$$\frac{MTBF_{A2}}{MTBF_{A1}}$$

It follows, as shown below, that this statistic will underestimate R as given by equation 1.

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$$\text{Assume } AF_2 > AF_1 \qquad \text{Then } \frac{AF_2}{AF_1} > 1$$

$$R = \frac{MTBF_{F2}}{MTBF_{F1}} = \frac{AF_2 \times MTBF_{A2}}{AF_1 \times MTBF_{A1}}$$

$$\frac{MTBF_{F2} \times MTBF_{A1}}{MTBF_{F1} \times MTBF_{A2}} = \frac{AF_2}{AF_1} > 1$$

$$\frac{MTBF_{F2}}{MTBF_{F1}} > \frac{MTBF_{A2}}{MTBF_{A1}}$$

$$\therefore \ R > \frac{MTBF_{A2}}{MTBF_{A1}}$$

Since $MTBF_{A2}/MTBF_{A1}$ is less than the true amount of product life change, the statistic used to estimate $MTBF_{A2}/MTBF_{A1}$ will consistently underestimate the true amount of change.

Although the invention is described herein using primarily HALT stress tests, it will be appreciated by those skilled in the art that modifications and changes may be made without departing from the spirit and scope of the present invention. As such, the method and apparatus described herein may be equally applied to any accelerated stress testing designed to expose product defects early in the product development process.